Liquid-metal erosion studies in IIAX (Ion-surface Interaction Experiment)

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Outline of Talk

- Scope of liquid metal erosion work in IIAX
- Experimental setup of IIAX (Ion-surface Interaction Experiment)
- Measurements and modeling of liquid lithium sputtering dependence with temperature
- Surface coverage effects on lithium sputtering
- Lithium erosion and its impact on PFC viability
- Conclusions and Future Work

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Scope of Experimental Work in IIAX

Liquid Lithium	Eo (eV) 200-1000	T (°C) 25-425	D-treated	Non D-treated
H^+	✓.	✓.	✓.	
D^+	✓.	✓.	✓.	✓.
He^+	✓.	✓.	✓.	✓.
Li^+	✓.	✓.	✓.	

Liquid Tin-lithium	Eo (eV) 200-1000	T (°C) 25-425	D-treated	Non D-treated
D^+	✓.	✓.	✓.	
He^+	✓.	✓.	✓.	✓.
Li^+	✓.		✓.	

Y_{sp}^+ for liquid lithium	Eo (eV) 200-1000	T (°C) 25-425	D-treated	Non D-treated
H^+, D^+, He^+, Li^+	✓.	✓.	✓.	✓.

Y_{sp}^+ for liquid tin-lithium	Eo (eV) 200-1000	T (°C) 25-425	D-treated	Non D-treated
H^+, D^+, He^+, Li^+	✓.	✓.	✓.	✓.

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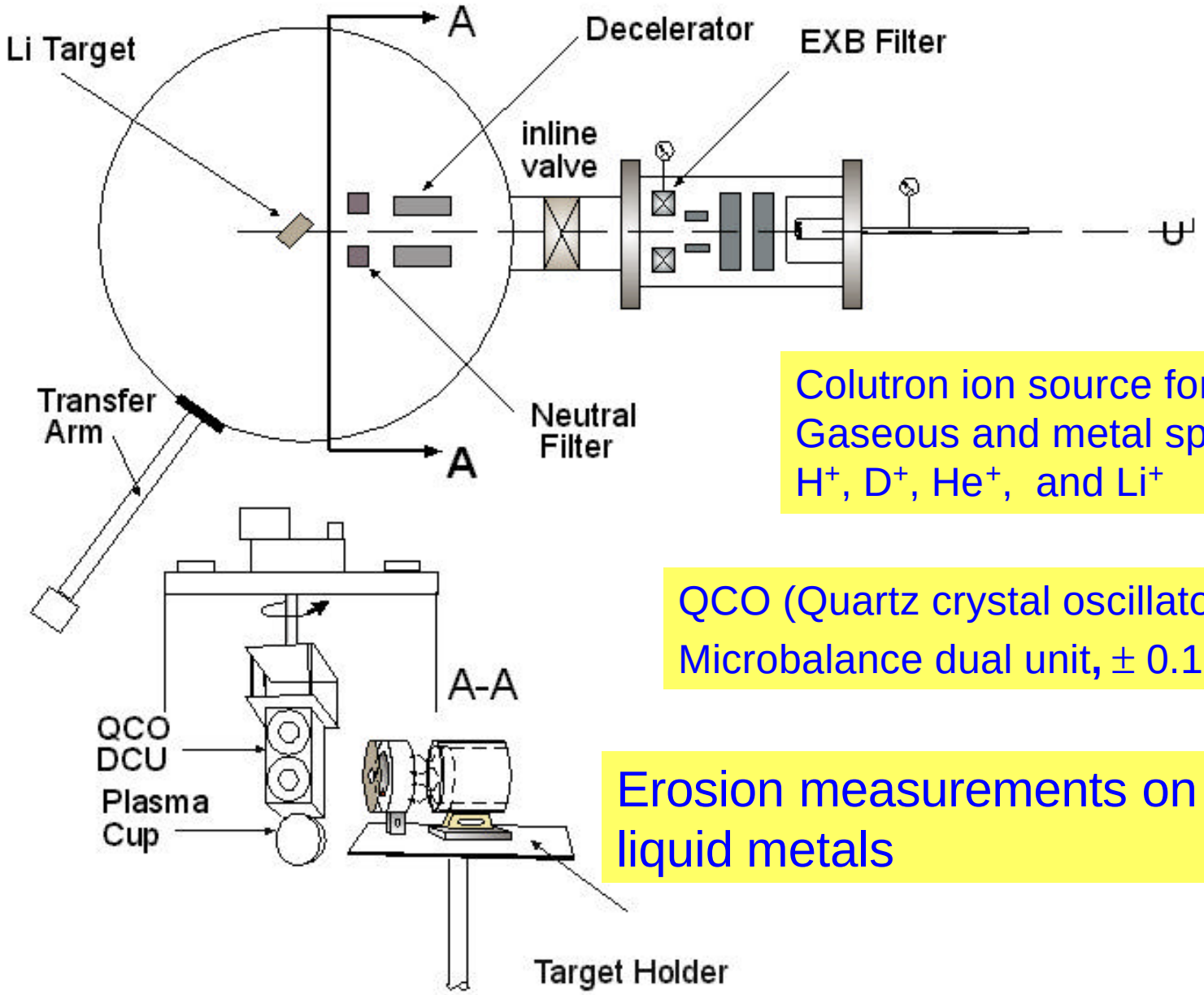

Colutron ion source for both Gaseous and metal species: H^+, D^+, He^+, and Li^+

QCO (Quartz crystal oscillator Microbalance dual unit, ± 0.1 Å)

Erosion measurements on static liquid metals

J.P. Allain, M.R. Hendricks and D.N. Ruzic, J. Nucl. Mater. 290-293 (2001) 180

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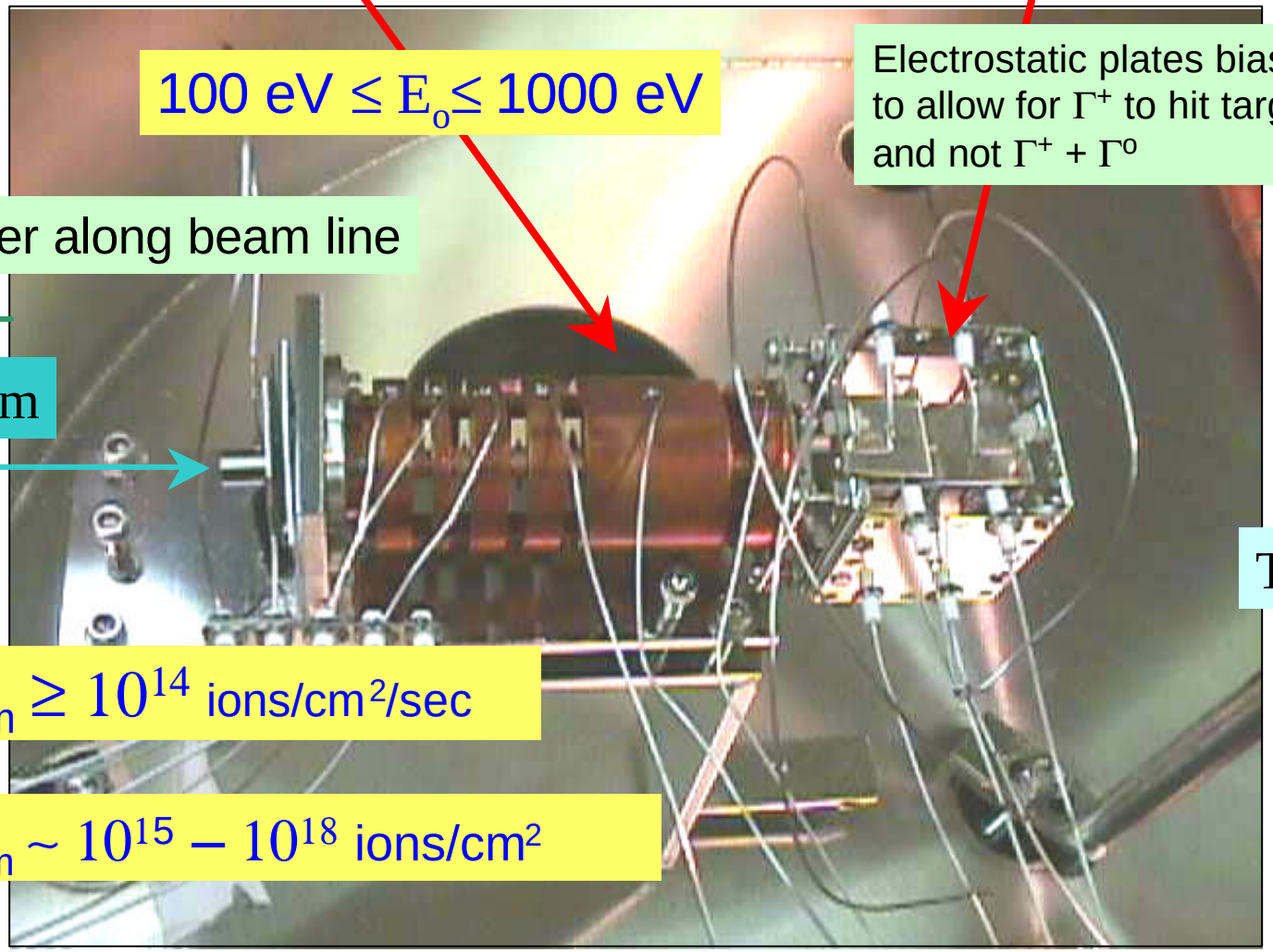
Decelerator and Neutral Filter



100 eV ≤ E_o ≤ 1000 eV

Electrostatic plates biased to allow for Γ^+ to hit target and not $\Gamma^+ + \Gamma^o$

E X B filter along beam line

Ion Beam

Target

$\Gamma_{ion\ beam} \geq 10^{14}$ ions/cm^2/sec

$\Phi_{ion\ beam} \sim 10^{15} - 10^{18}$ ions/cm^2

J.P. Allain, M.R. Hendricks and D.N. Ruzic, J. Nucl. Mater. 290-293 (2001) 180

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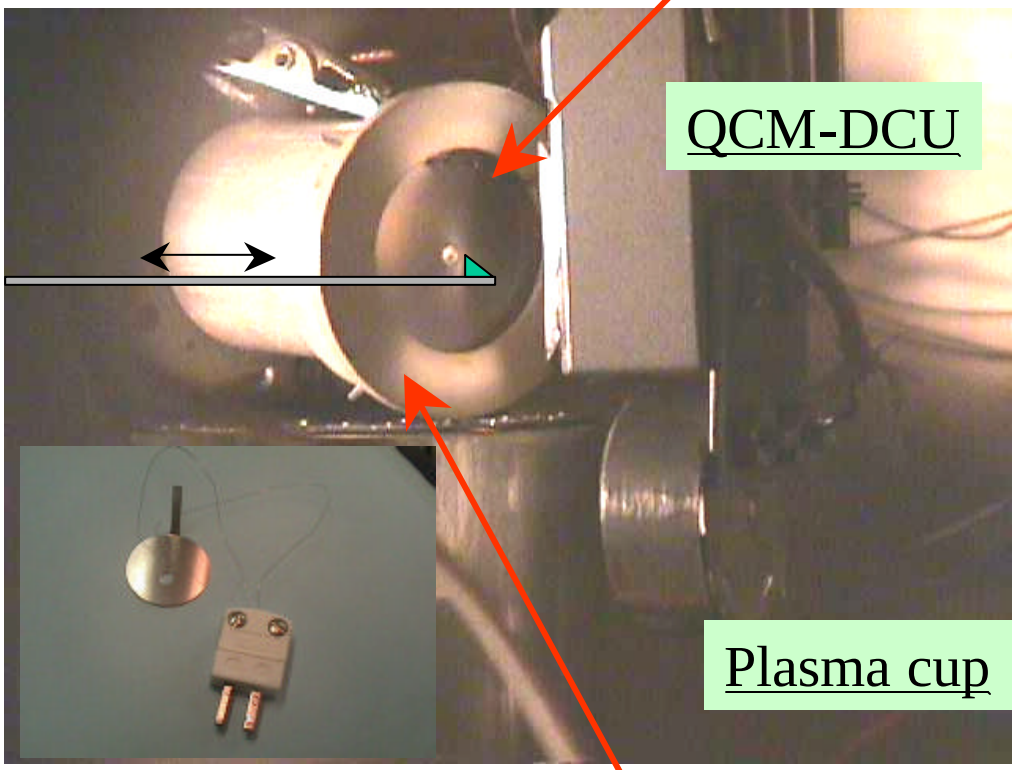
In-situ cleaving arm design and HV heater

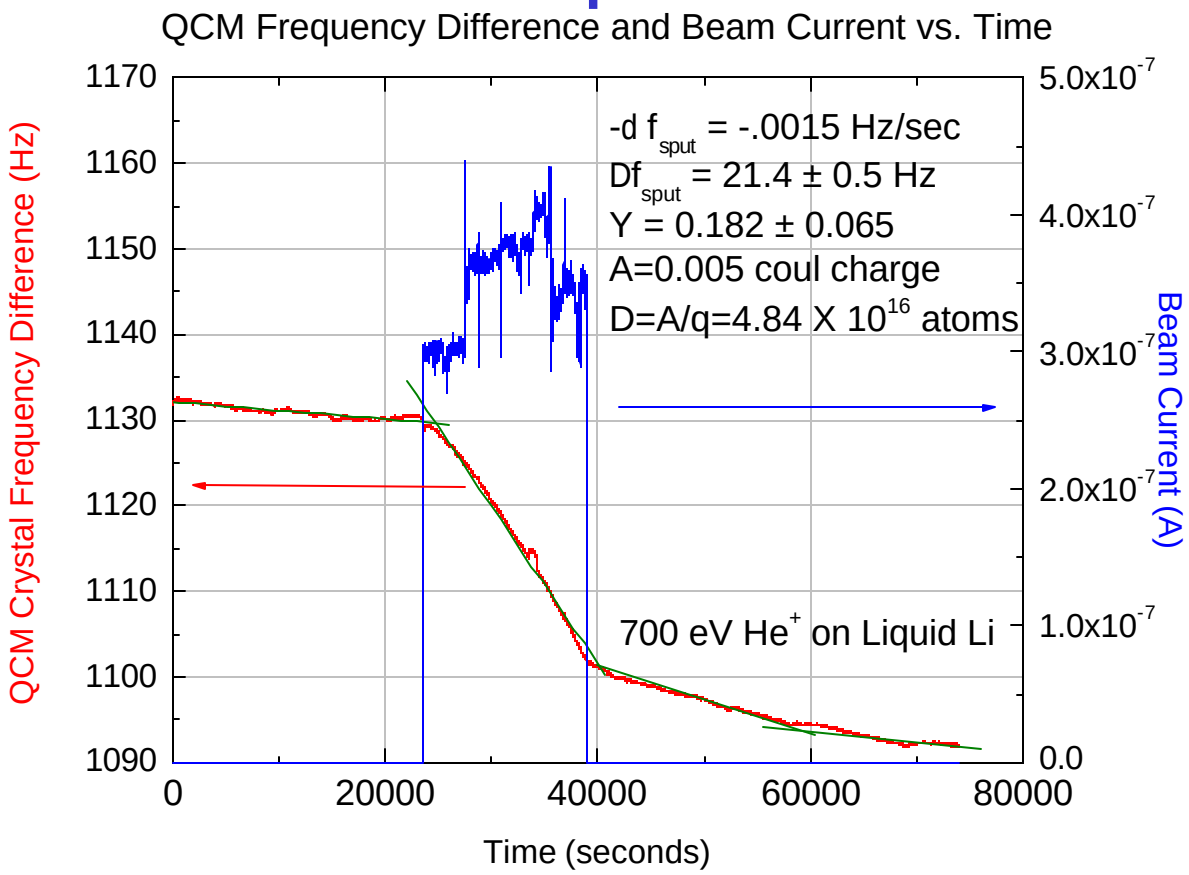
- Cleaving arm is designed to remove thin oxide layer formed on Li layer of liquid lithium sample
- After slag layer is removed surface is treated with a fluence of 10^{17} D/cm^2 before each data point is taken at each temperature



A HV heater is installed inside a BN cup.

QCM frequency difference and IIAX beam current time plots

- Before liquid target is irradiated with ion beam, an evaporation flux measurement is completed
- QCM frequency difference slope increases when beam hits target measuring evap + sputtering fluxes
- When beam is off, some oxidation follows until original evap flux is obtained



$$-df_{sput} = \left| df_{sput+evap} - df_{evap} \right|$$

$$Y = \frac{1}{Df_i S \Omega m_{Li2O}} \frac{\Delta f}{f_{final}} M_{crystal} \left(1 + R_j Y_j \Omega_j\right)$$

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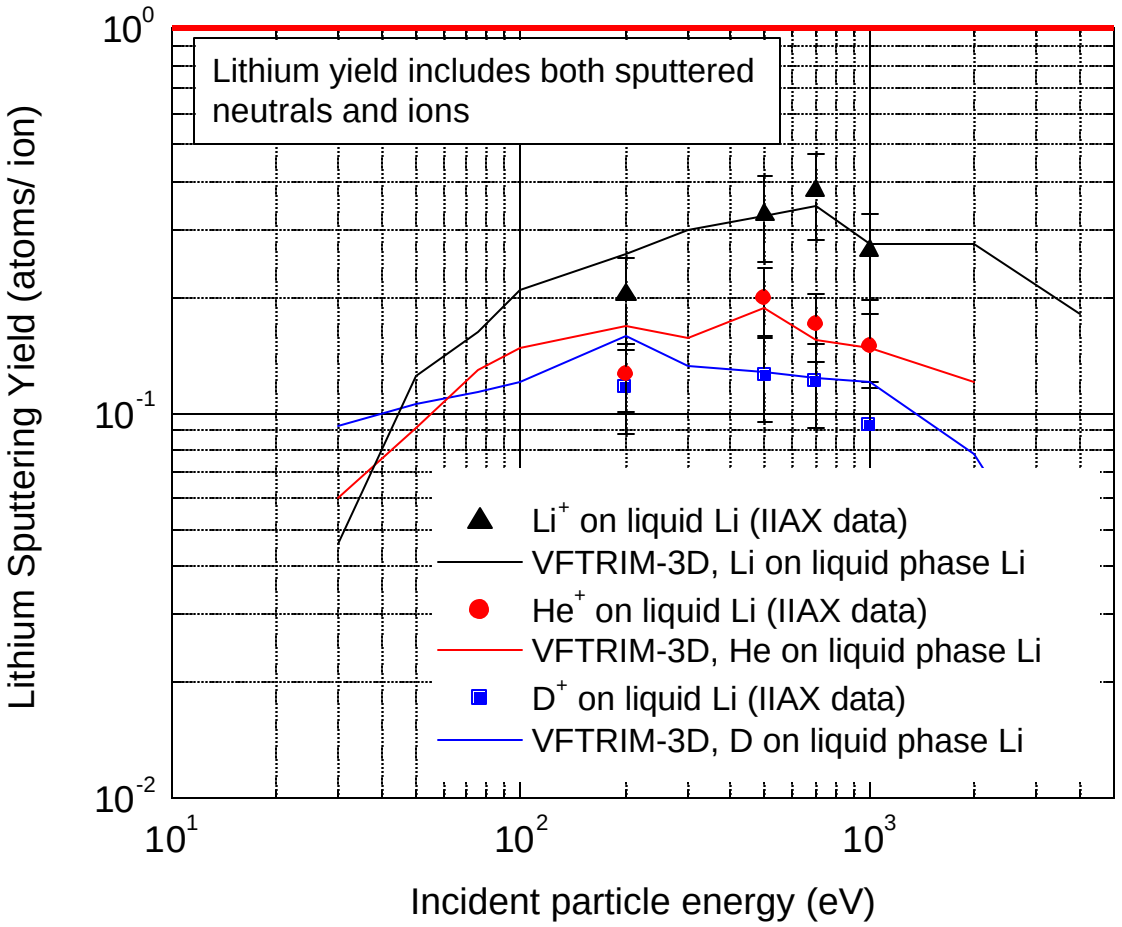
IIAX experimental and modeling data on liquid lithium erosion

- D-treated lithium yields are below unity
- Data taken at 45-degree incidence and 200 °C surface temperature[1]
- Sec. Sputtered ion fraction is 65-70%
- T_m = 180 °C



1. J.P. Allain, M.R. Hendricks and D.N. Ruzic, J. Nucl. Mater. 290-293 (2001) 180

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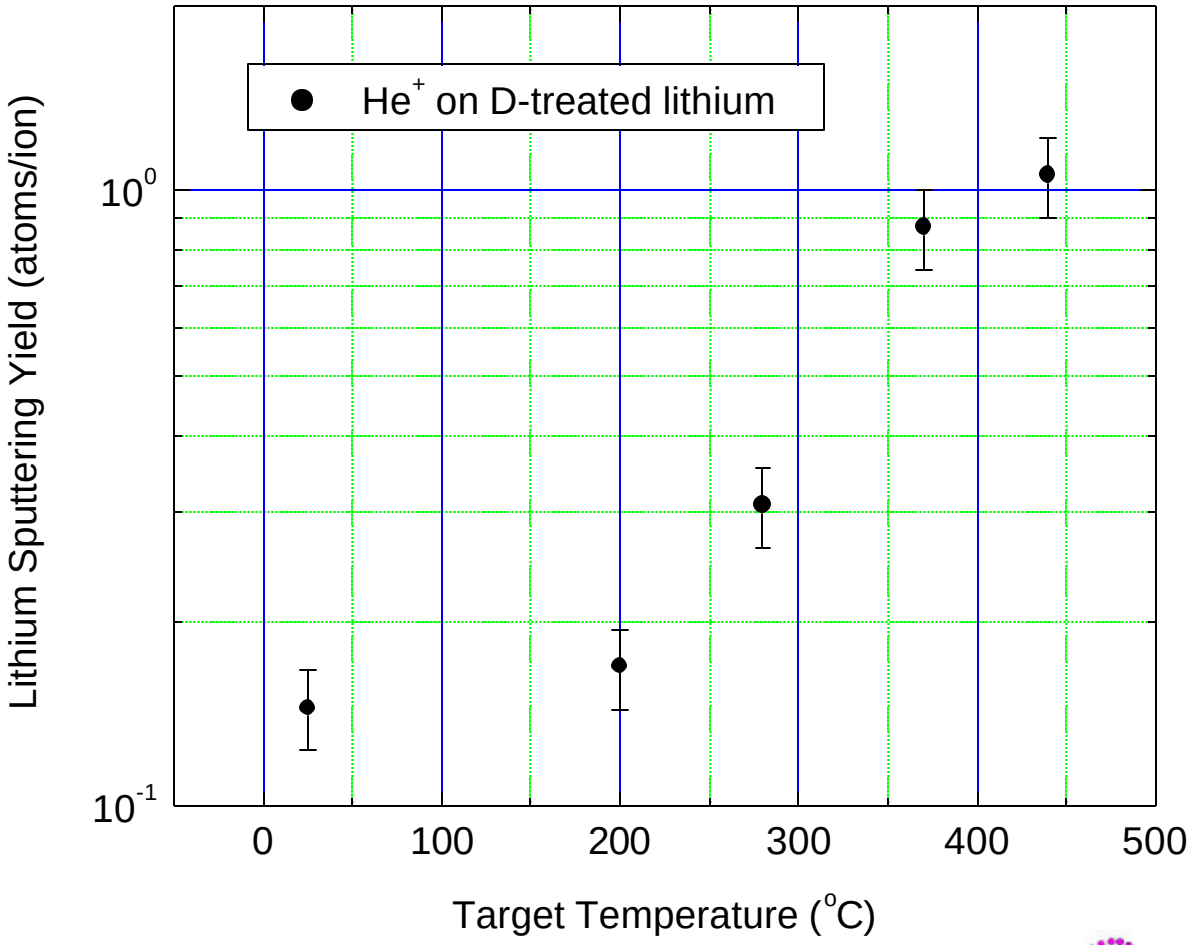
IIAX data on lithium sputtering yield temperature dependence for lithium and tin-lithium targets

- Enhanced erosion of lithium measured for temperatures much higher than melting temp. for both lithium and tin-lithium
- Models for liquid lithium with smooth surface in VFTRIM-3D show several temperature-dependent mechanisms[1]



1. J.P. Allain and D.N. Ruzic, to be submitted to Appl. Phys. Lett 2002

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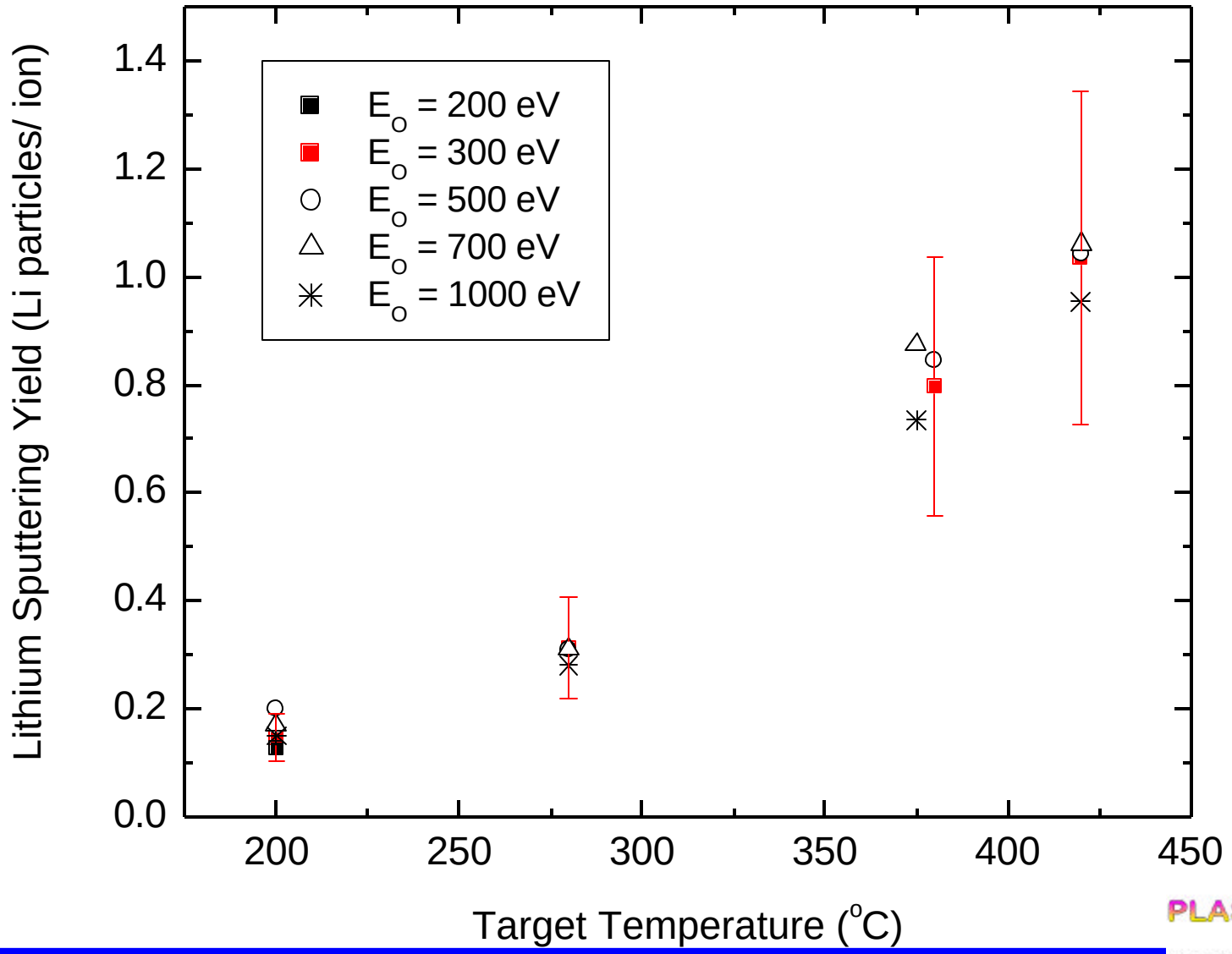
He^+ bombardment of liquid Li



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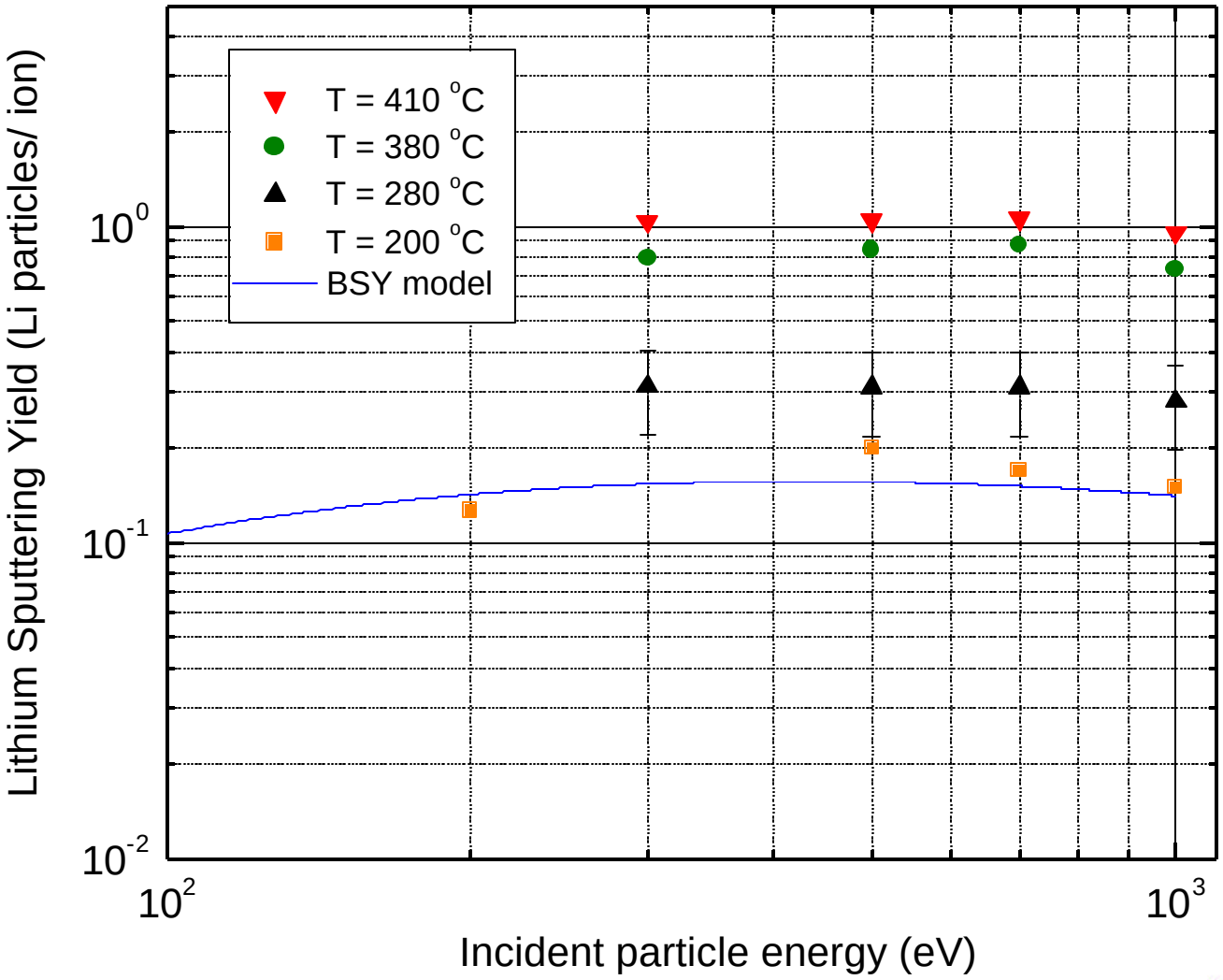
He^+ bombardment of liquid Li



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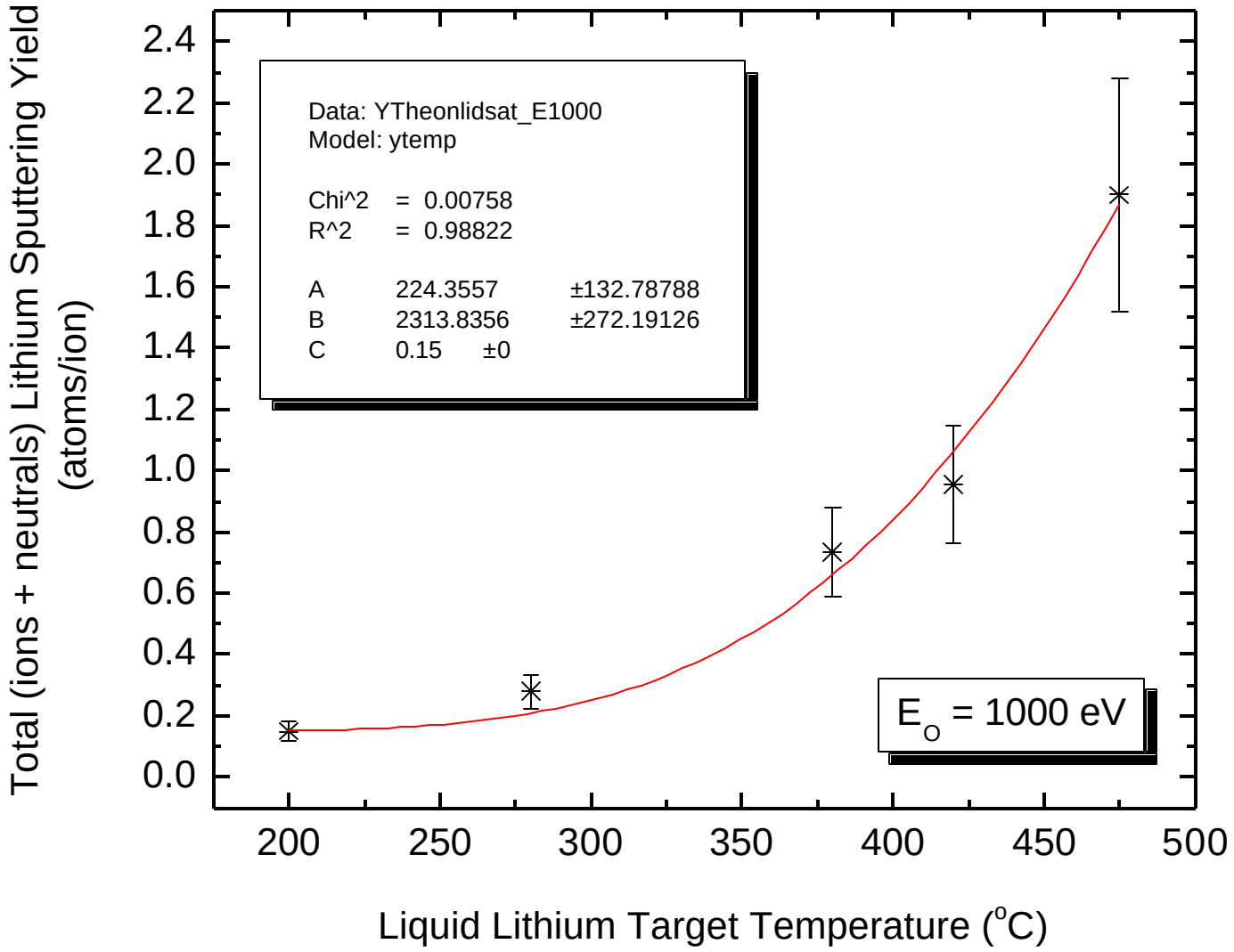
He^+ on liquid Li empirical fits



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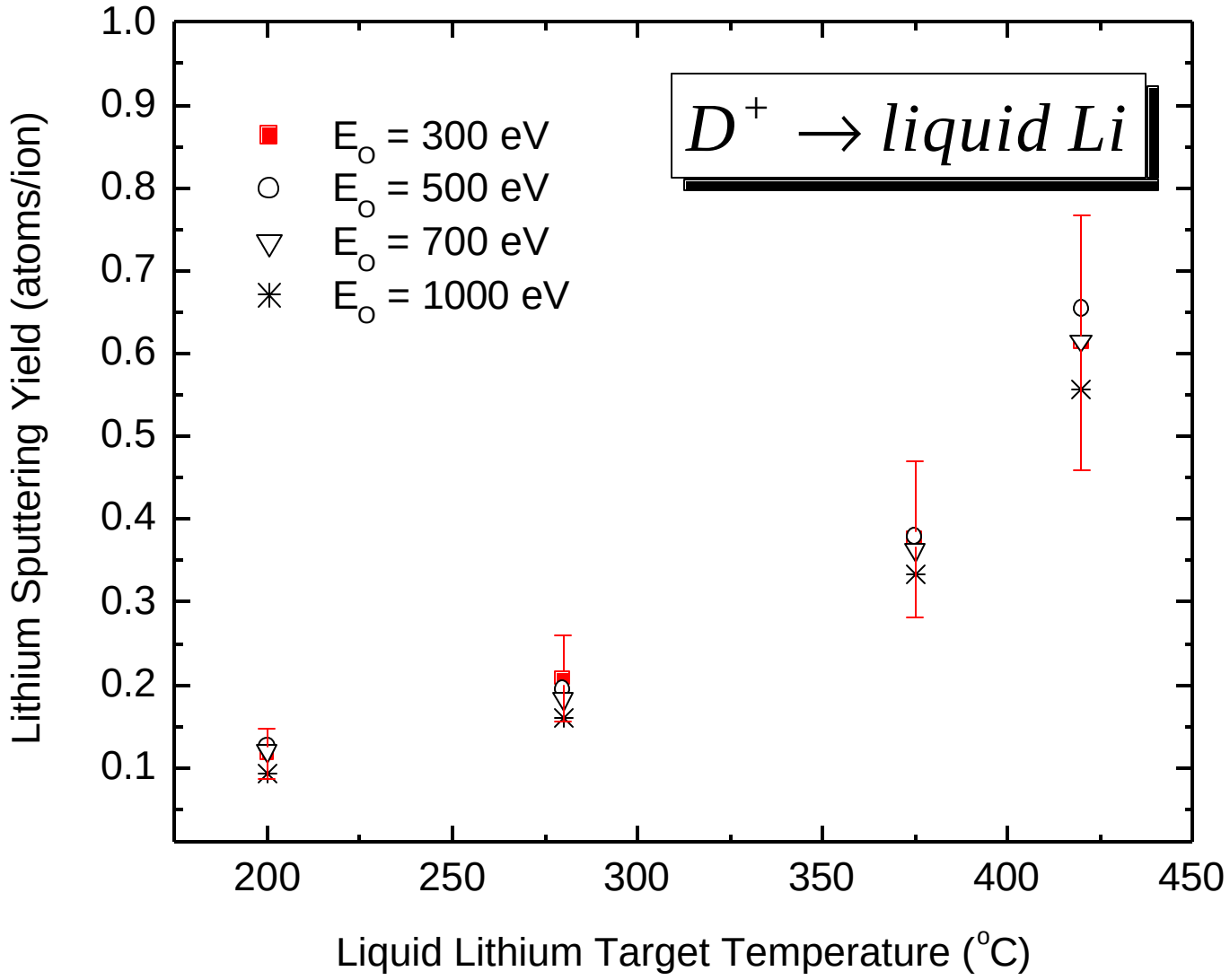
D^+ bombardment of liquid Li



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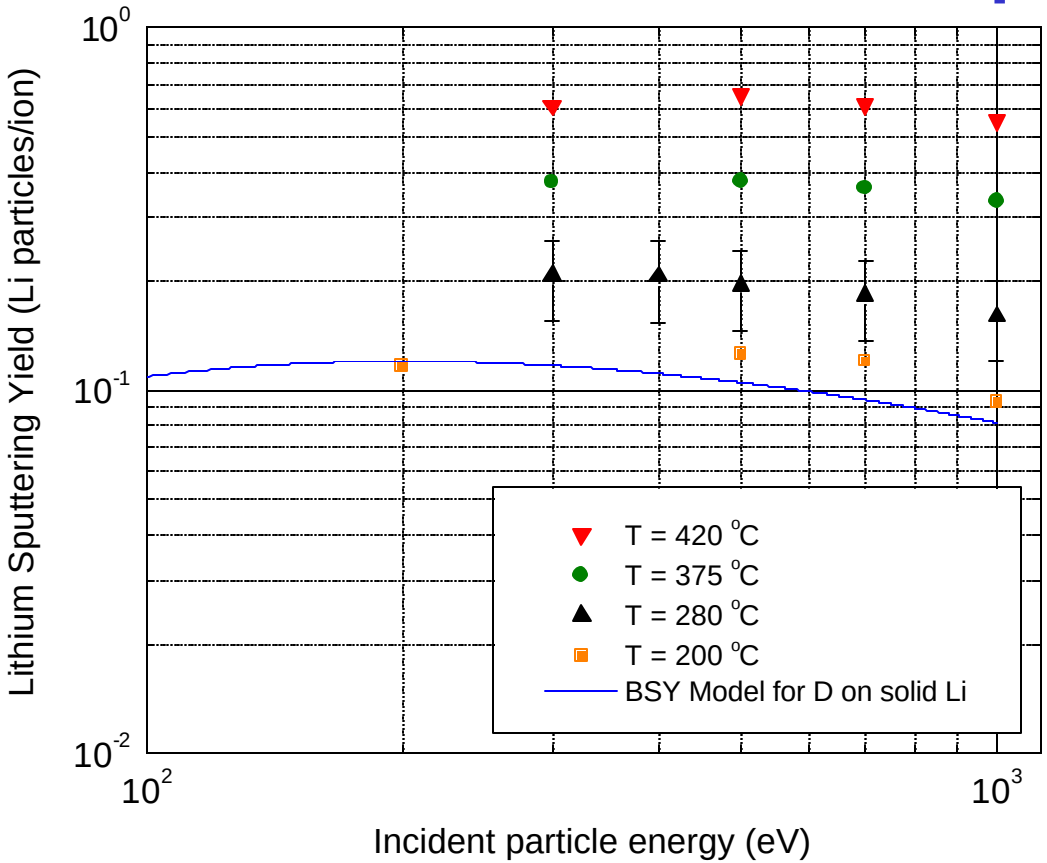
D^+ bombardment of liquid Li



- Angle of incidence is equal to 45-degrees
- Solid blue line corresponds to linear sputtering theory
- Enhanced erosion measured at energies 300-1000 eV

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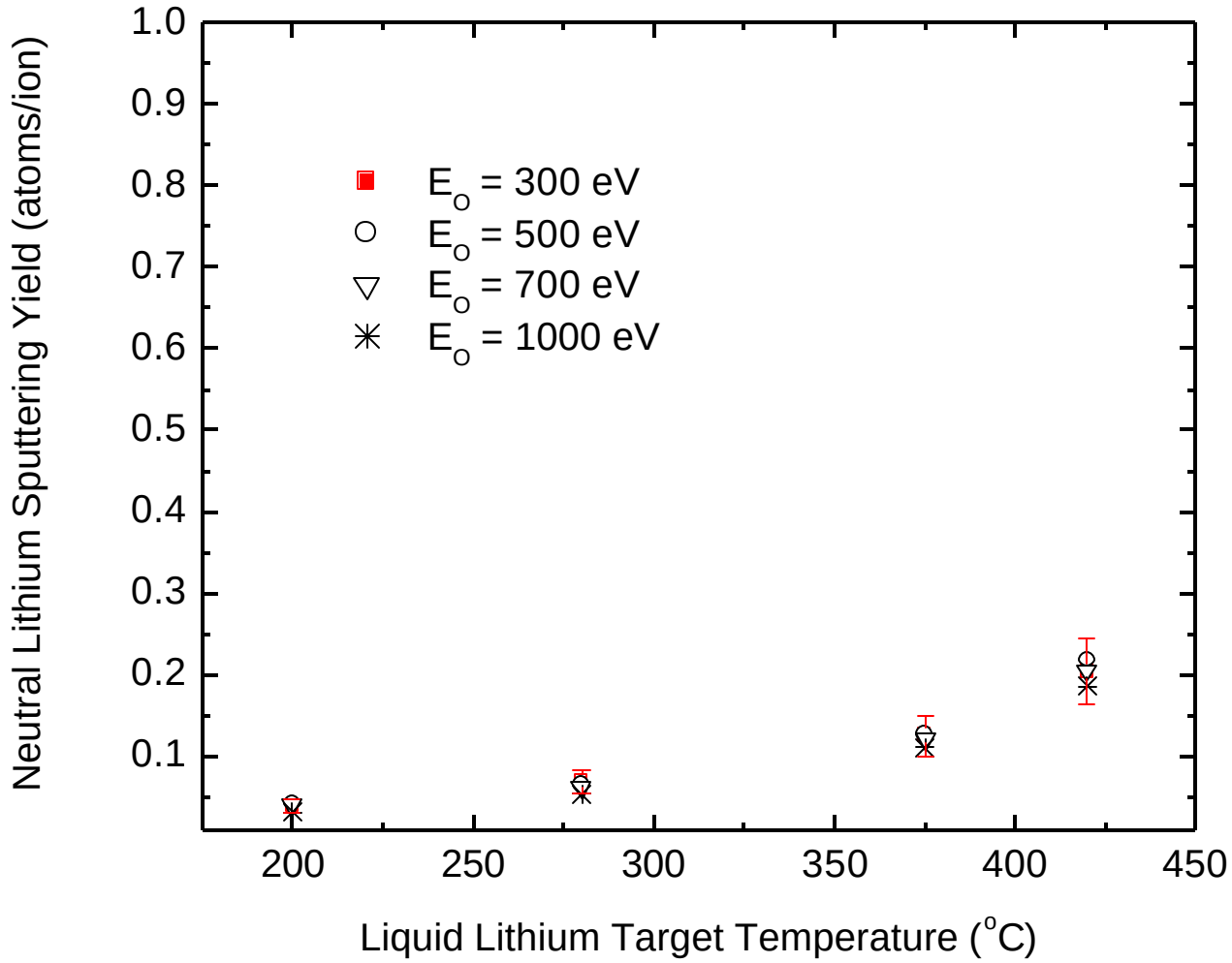
D^+ bombardment of liquid Li with sputtered neutrals yield only



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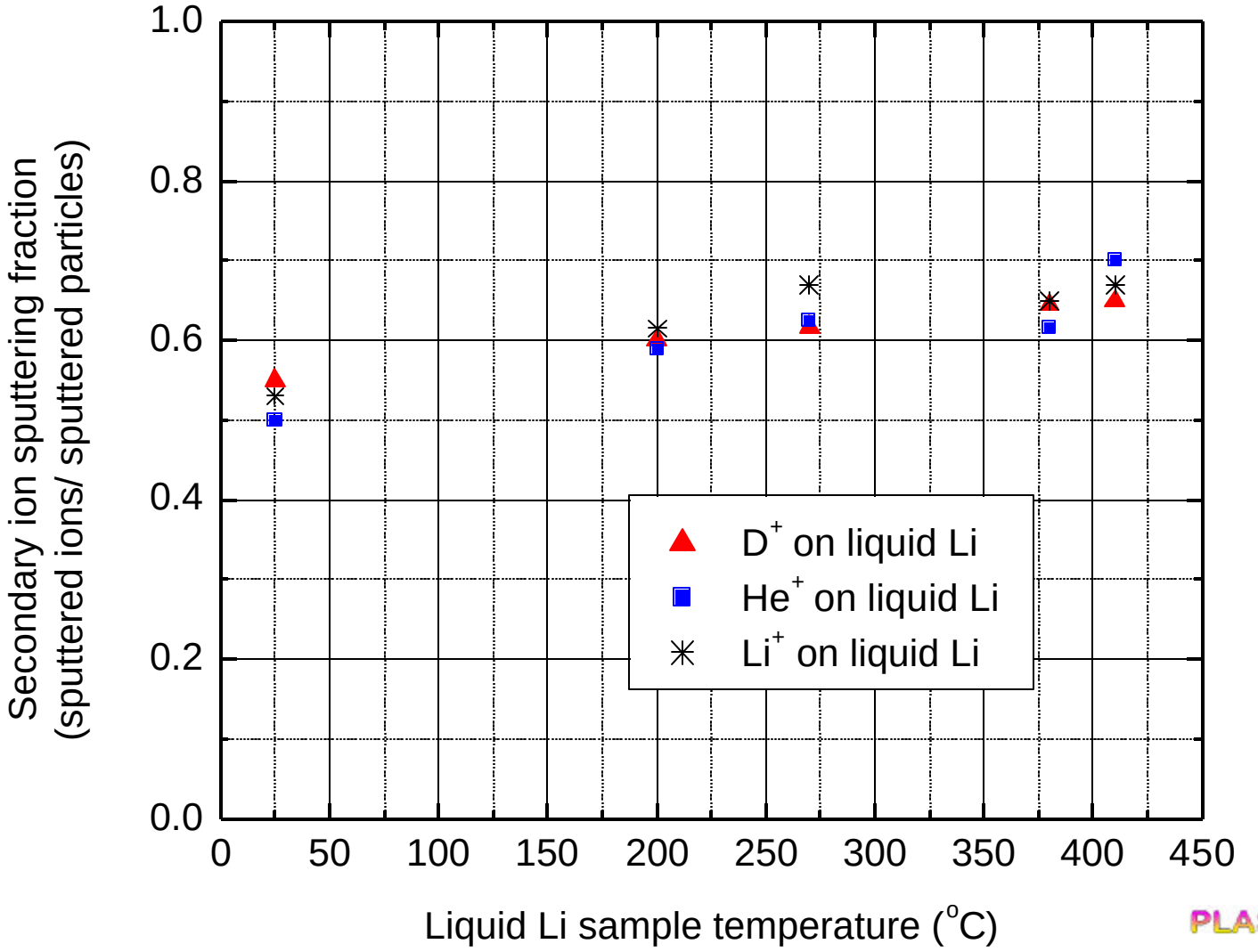
Secondary ion sputtering fraction (Y^{+}_{sp}) dependence on target temperature for Liquid Lithium



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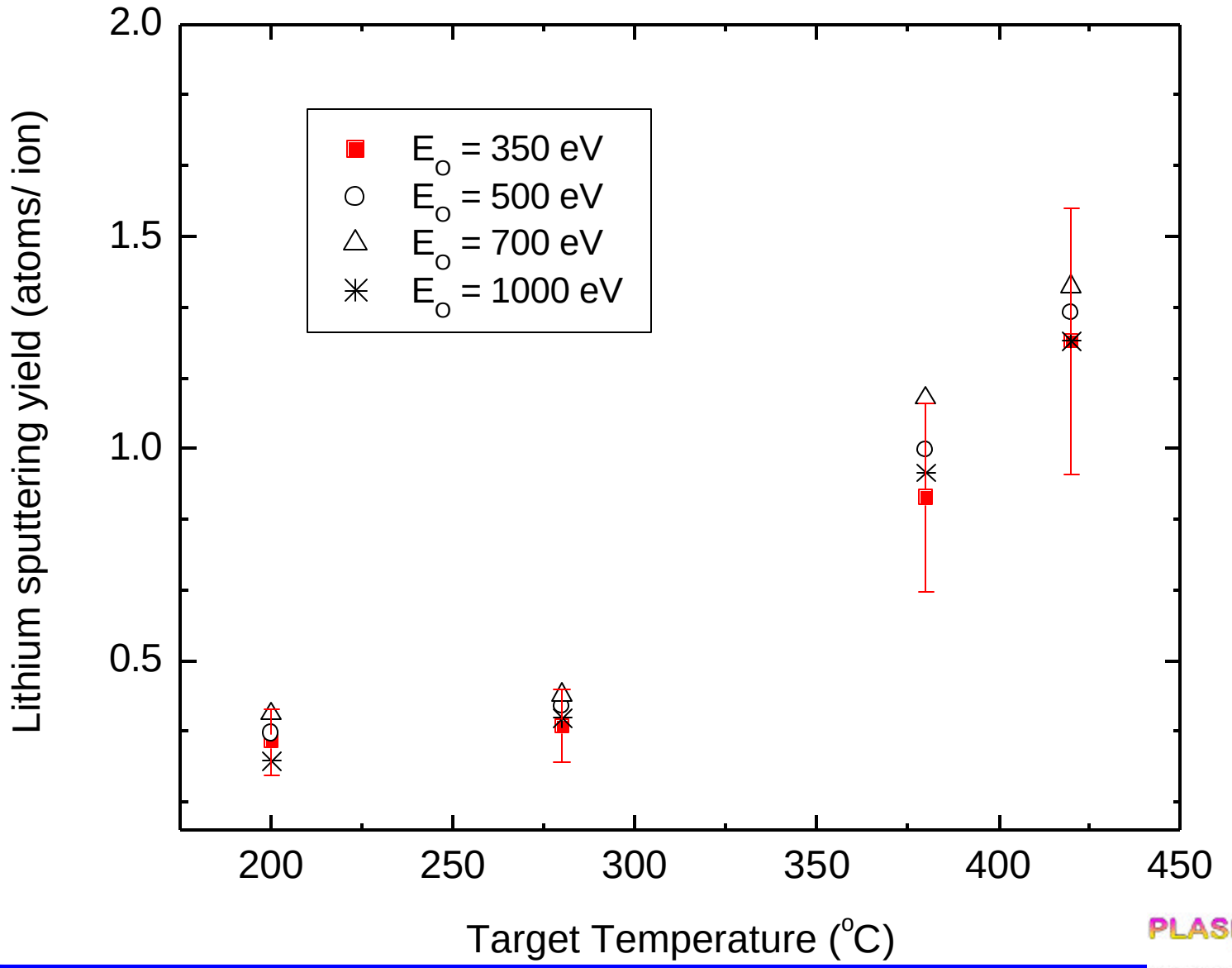
Li^+ bombardment of liquid Li



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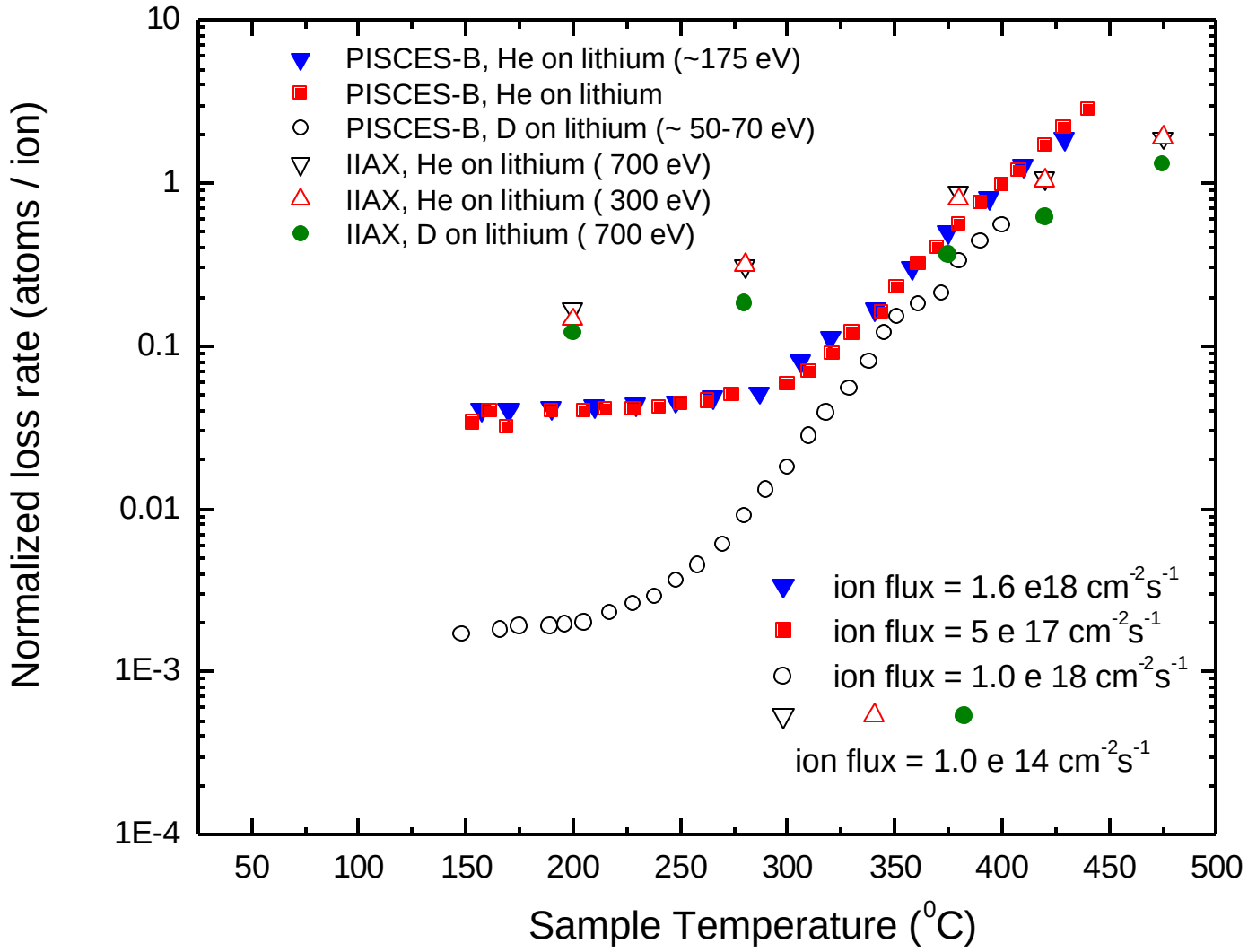
IIAX and PISCES-B temperature-dependence lithium erosion data



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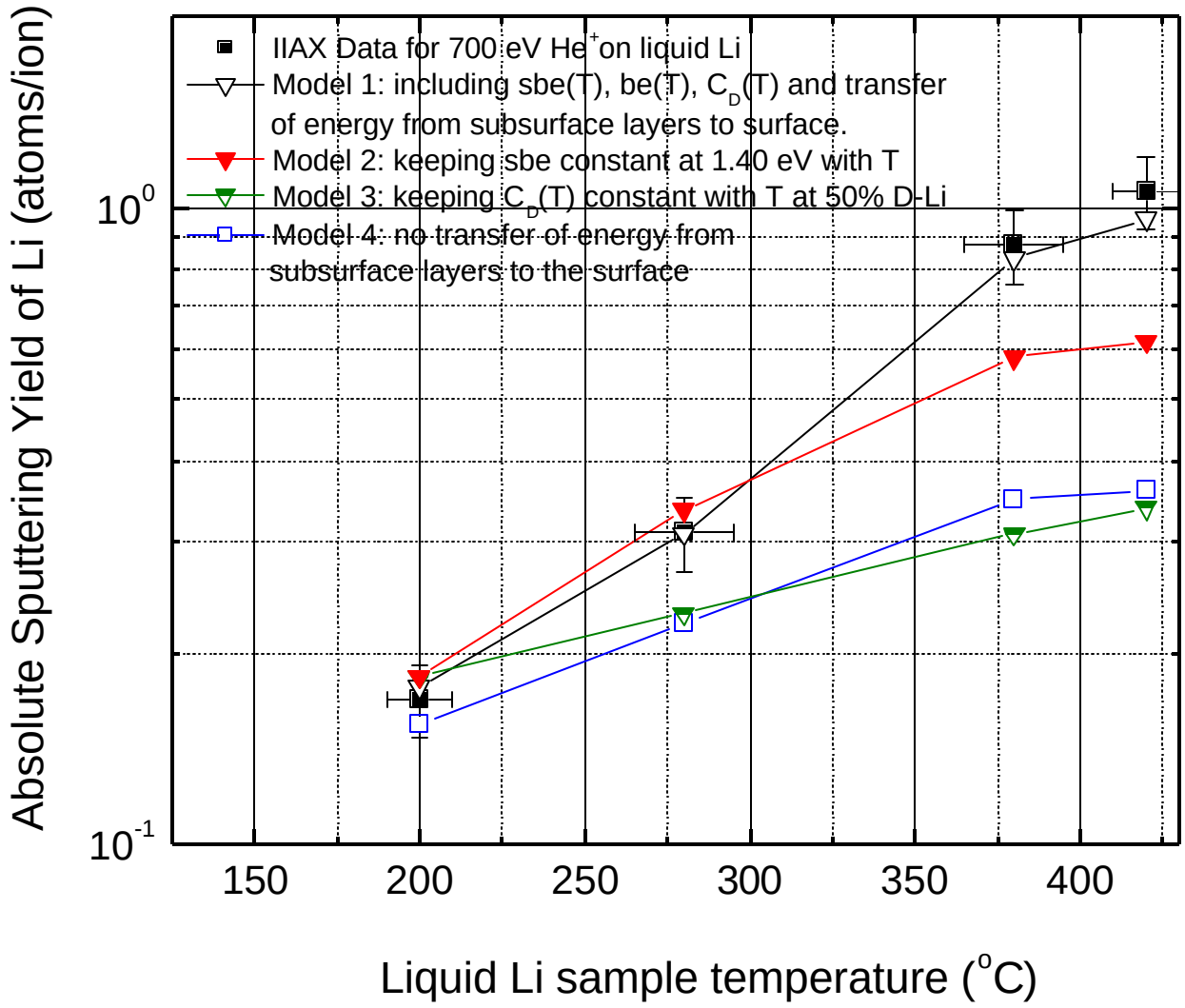
He^+ bombardment of liquid lithium temperature dependence with VFTRIM-3D models



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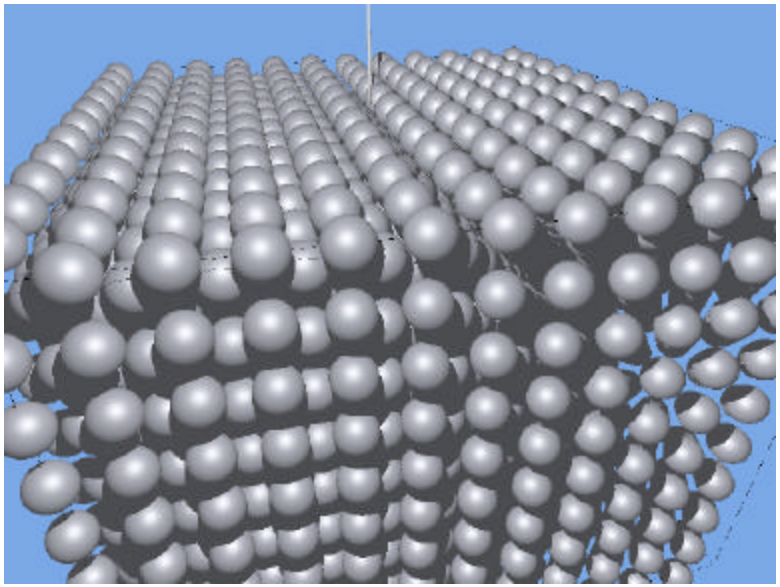
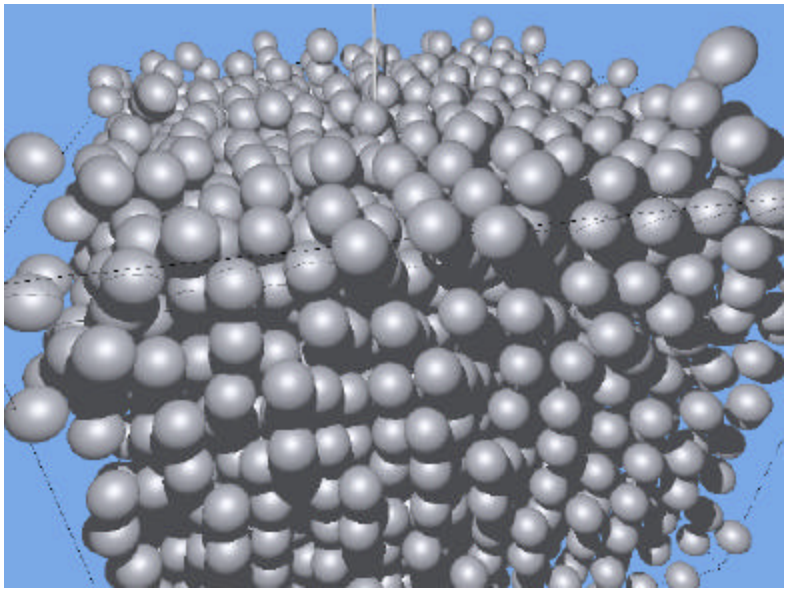
Limitations of BCA-based models and need for Molecular Dynamics studies at low energies

- At energies less than 1 keV, for liquids, BCA models may fail to completely describe irradiation damage and its relation to erosion enhancement.
- Molecular dynamics simulations can account for transfer of energy to all atoms as opposed to a single binary collision.
- MD studies are now beginning at the U of I in coordination with R. Averback's group.
- In addition collaboration with S. Krasheninnikov is also planned.

Liquid lithium simulation setup





- Temperature control is achieved by using a simple velocity scaling technique at each time step[1-3] to maintain the desired temperature at the edges of the surface.
- The resulting target surface is an amorphous liquid lithium surface 42.2 by 42.2 Å and 34.2 Å deep.

1. L. V. Woodcock, Chem. Phys. Lett. **10**, 257 (1970).
2. D. J. Evans, Mol. Phys. **37**, 1745 (1979).
3. T. Schneider and E. Stoll, Phys. Rev. B **13**, 1216 (1976).

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Surface treatment and chemical state: its influence on lithium sputtering

- In solid lithium sputtering the effect of D-treatment on lithium sputtering is important.
- In liquid phase the effect seems to be relevant at temperatures near the melting point.
- For temperatures higher than about 300 °C, these effects diminish quite rapidly.
- Studies are continuing on determining at what minimum fluence and sample temperature does effect of D-treatment on lithium sputtering becomes irrelevant.
- In addition, determination of chemical state of lithium surface will be studied under these conditions for both sputtering and evaporation.

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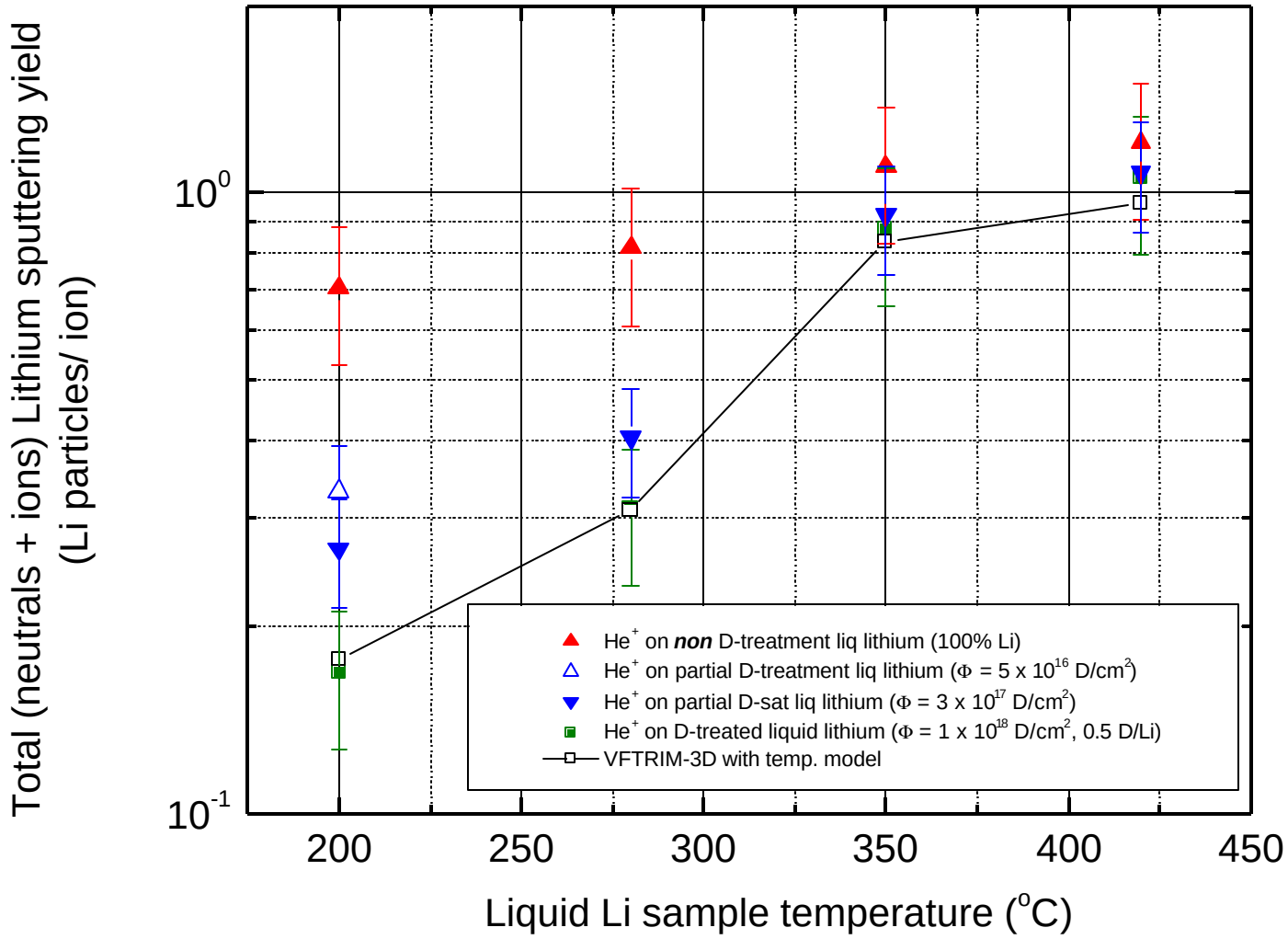
Deuterium coverage studies in IIAX as a function of temperature



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Tables with Li yields for 100% Li and 50% Li-D

- Conditions in table are for T ~ 200 °C
- Estimate of neutrals are according to Kotschenreuter's assumed 1/3 ion fraction for column 1 and IIAX measured ion fraction of ~ 2/3 for column 2.
- Angle of incidence in column 1 is 70°. In column 2, 45° is used to more accurately represent expected angle of incidence†.

Li yields	M. Kotschenreuter	J.P. Allain, et al.
500-700 eV D^+ sputtering (100% Li)	0.2-0.4 (neutrals: 0.133-0.267)	0.2-0.3 ± 0.06 (neutrals: 0.067-0.1)
500-700 eV D^+ sputtering (0.5 D/Li)		0.121-0.126 ± 0.03 (neutrals: 0.040-0.042)
500-700 eV self-sputtering (100% Li)	1.35-2.0 (neutrals: 0.9-1.33)	0.872-1.04 ± 0.17 (neutrals: 0.291-0.347)
500-700 eV self-sputtering (0.5 D/Li)		0.329-0.376 ± 0.082 (neutrals: 0.110-0.125)

†J. Brooks, et al. J. Nucl. Mater., 290-293 (2001) 185
J. Brooks, Phys Fluids B – Plasmas, **2** (8) (1990) 1858.

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Conclusions

- Solid and liquid lithium sputtering yields measured in IIAX-UIUC show less-than unity self-sputtering yields.
- Measurements for D^+, He^+ and Li^+ bombardment of liquid lithium for temperatures between 200-450 °C and energies between 200-1000 eV have been completed.
- These measurements show lithium erosion enhancement for all cases mentioned.
- Further studies needed with molecular dynamics to study enhanced erosion phenomena.
- Even for cases of non D-treated lithium surfaces or 100% Li in the liquid state, erosion is tolerable up to temperatures near 400 °C.

Future Work Plan

- Further study on bubble formation effects in liquid lithium sputtering as well as additional measurements on liquid lithium evaporation.
- Continue study of temperature-enhanced erosion of liquid lithium and development of a self-consistent model using molecular dynamics.
- Continue study of surface treatment effects on liquid lithium sputtering.
- Study Sn sputtering in solid and liquid phase.
- Continue to study difference in IIAX and PISCES-B data on lithium erosion.

Acknowledgements

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- J.N. Brooks, A. Hassanein, R. Bastasz, R. Causey, M. Baldwin, S. Krasheninnikov and R. Averback for helpful discussions
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  - Andy Simnick

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